PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Evaluation of Uncertainties in Ground Motion Estimates for Soil Sites

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**A report to the PEER Program of
Applied Earthquake Engineering Research on
Lifeline Systems**

**The financial support of the sponsor organizations including
the Pacific Gas & Electric Company (PG&E),
the California Energy Commission (CEC), and the
California Department of Transportation (Caltrans) is acknowledged.**

PEER UTILITIES PROGRAM
REPORT NO. 2000/04

TASK 5

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by

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Research supported by the PEARL sponsor organizations including the Pacific Gas & Electric Company, the California Energy Commission, and the California Department of Transportation under Award Number 09566.

Report No. UCLA/CEE-2000/01

Department of Civil & Environmental Engineering
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Los Angeles, California

January 2000

Abstract

For a given seismic source, ground motions at soil sites can be estimated using either soil attenuation relationships, or ground response analyses with input motions scaled to match specified spectral ordinates from rock attenuation relationships. When engineers perform ground response analyses, it is with the expectation that accounting for nonlinear sediment response will improve the accuracy and reduce the uncertainty in estimated ground motions. This study investigates such benefits of ground response analyses as a function of site condition. A total of 36 strong motion sites are investigated, with roughly equal representation in the site categories of: (1) shallow stiff soil, (2) moderate-depth stiff soil, (3) deep stiff soil, and (4) soft clay.

Procedures were developed for selecting and scaling suites of input motions for ground response analyses that incorporate key source and path information such as magnitude, distance, and rupture directivity. The median of the input suite is scaled to match a “best estimate” target spectrum established from a rock attenuation relationship modified to incorporate an event term, rupture directivity effects (if applicable), and weathered rock correction factors. Since only the median of the suite is scaled to match the target, the aleatory uncertainty of source/path is retained. The results of ground response analyses using these input motions are expressed statistically in the form of medians and standard error terms. These statistical quantities are the ground response counterparts to the median and standard error of spectral ordinates from a soil attenuation relationship.

Residuals between recorded and estimated motion were calculated to elucidate trends in the results of each ground motion estimation procedure across geotechnical site categories. For $T < 1$ s, ground response analyses are found to improve the accuracy of ground motion predictions relative to attenuation in all site categories. However a positive bias in median ground response estimates is found for most site categories, indicating a systematic underprediction of ground motion that is not yet fully understood. In addition, the uncertainty in the residual of the estimated ground motions is large for stiff soil sites, indicating that source/path effects are "randomly" and significantly varying the motions from site-to-site. Conversely, for soft clay sites, the standard error of ground response estimates is small, indicating a strong and systematic influence of ground response that is reasonably well captured by the analysis. For $T > 1$ s, substantial positive bias is observed in results for moderate to deep stiff soil sites, which may be a basin effect. In light of the observed biases, recommendations on the interpretation of ground response results are provided.

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Acknowledgements

We would like to thank Nancy Smith and Paul Somerville URS Greiner Woodward Clyde, Pasadena Office, for providing rupture directivity parameters for strong motion stations. Thanks are also extended to Walt Silva of Pacific Engineering and Analysis and Norm Abrahamson of PG&E for helpful comments made in numerous discussions about this topic. We appreciate the efforts of Andrew Liu of UCLA, who helped prepare input files for ground response studies. The financial support of the PEARL sponsor organizations including the Pacific Gas and Electric Company (PG&E), the California Energy Commission (CEC), and the California Department of Transportation (Caltrans) is acknowledged.

1.0 INTRODUCTION

For a given seismic source, ground motions at soil sites are generally estimated using either soil attenuation relationships, or ground response analyses with input motions scaled to match specified spectral ordinates from rock attenuation relationships. In either case the attenuation relationships are relied upon to capture source and path effects on ground motion. Site response analyses are performed to account for the nonlinear response of shallow sediments, and hopefully reduce the uncertainty in the estimated ground motions on soil.

The relative influence of source/path and site response effects on residuals between recorded and estimated soil site ground motions have been investigated by numerous researchers. Lee (1996) examined the southern California strong motion inventory for soil and rock sites compiled by SCEC. He found that residuals from the Abrahamson and Silva (1997) attenuation relationship at short and intermediate periods are not systematically high or low for soil sites with multiple ground motion recordings, implying that "random" source/path variability is far more pronounced than the site response effect (which should produce a fairly consistent residual across multiple events). Other researchers have found consistent and pronounced site response effects through comparisons of strong motions from a particular event recorded at similar site-source distances and azimuths, but different site conditions (Seed et al., 1987; Idriss, 1990; Seed and Dickenson, 1996; Chang, 1996; Darragh and Idriss, 1997; Woodworth et al., 1998). Site effects during specific events have also been identified from statistical studies of the regional variations in spectral ordinates across different geologic conditions (Borcherdt and Gibbs, 1976; Borcherdt, 1994; Rodriguez-Marek et al., 1999). Analytical studies by Roblee et al. (1996) invoking a stochastic finite source model and an equivalent-linear formulation for site effects have shown that variability in site effects arising from uncertainty in soil properties can overwhelm the variability in source and path effects. The relative significance of site response variability as compared to source/path variability increased with decreasing site-source distance, and increasing site period.

The disconnect between the findings from Lee's interpretation of southern California data and the significant site effects found from other empirical and analytical studies indicates a clear need to identify the geologic conditions where site effects cause ground motions on soil to significantly and consistently differ from the predictions of soil attenuation relations. Accordingly, this study evaluates the "benefit" gained from ground response studies as compared to the simple use of soil attenuation relations as a function of the general geologic conditions underlying a site. Specifically, we compare the ability of soil attenuation relations and carefully performed ground response studies to capture the 5%-damped spectral accelerations for 36 sites with widely varying geologic conditions that have recorded strong ground motion. The intent is to provide to earthquake engineers a rational basis for deciding when costly site exploration work and ground response analyses are justified from the standpoint of their ability to reduce the residuals and the uncertainty in ground motion estimates on soil.

The report begins in Section 2.0 by describing the geotechnical site classification scheme and site selection procedures used in this study. Sections 3.0 and 4.0 describe procedures for input motion selection and scaling, and performing ground response analyses, respectively. Section 5.0 presents statistical analyses of residuals between recorded and prediction ground motions for sites in various geotechnical categories. Section 6.0 presents results of sensitivity analyses investigating the significance of scaling procedures for input motions used in ground response analyses. Site data and site-specific analysis results are presented in Appendix B.

2.0 SITE SELECTION

The principal criteria used for site selection were: (1) at least one strong motion recording must be available at the site, (2) soil conditions at the site must be well characterized, including in situ measurements of shear wave velocity, and (3) the distribution of soil conditions across the locus of sites must include roughly equal numbers of shallow stiff soil sites, moderately deep stiff soil sites, deep stiff soil sites, and soft soil sites.

The grouping of sites according to soil conditions was made using a geotechnical site classification scheme that was introduced by Seed and Dickenson (1996) and modified by Rodriguez-Marek, et al. (1999). This classification scheme is presented in Table 1. Rodriguez-Marek, et al. (1999) performed event-specific regressions for the 1989 Loma Prieta and 1994 Northridge earthquakes, and found reasonably consistent trends in the attenuation for Category D sites (deep stiff soil), as demonstrated by error terms (σ) that were smaller than those obtained by grouping all soil sites together. In contrast, error terms for the C category (shallow stiff soil) were larger than those for the aggregate of soil sites. Based on these results, Rodriguez-Marek et al. suggested further subdivision of the C category may be appropriate, possibly based on 30 m shear wave velocity. They also noted that the data was too sparse to justify subdivision of the D category, but that soil depth, age, and soil type are likely significant. Idriss (1990) found fairly consistent trends in the Maximum Horizontal Accelerations (MHA) at E sites (soft clay) relative to nearby rock sites during the 1989 Loma Prieta earthquake. These results generally support the use of the classification scheme in Table 1, although the scatter within category C is of concern.

Table 1: Geotechnical site classification scheme proposed by Rodriguez-Marek et al. (1999)

Site	Description	Approx. Site Period (s)	Comments
A	Hard Rock	≤ 0.1	Crystalline Bedrock; $V_s \geq 5000$ fps
B	Competent Bedrock	≤ 0.2	$V_s \geq 2000$ fps or < 30 ft. (10 m) of soil. Most "unweathered" California Rock cases
C1	Weathered Rock	≤ 0.4	$V_s \approx 1000$ fps increasing to > 2000 fps, weathering zone > 30 ft. and < 100 ft.
C2	Shallow Stiff Soil	≤ 0.5	Soil depth > 30 ft. and < 100 ft.
C3	Intermediate Depth Stiff Soil	≤ 0.8	Soil depth > 100 ft. and < 200 ft.
D1	Deep Stiff Holocene Soil, either **C** (Cohesive) or **S** (Cohesionless)	≤ 1.4	Depth > 200 ft. and < 700 ft. Cohesive loosely interpreted. Tentatively use PI > 5% for the fines fraction. Cohesionless soils are those either with low fines content (i.e. < 15%) or with non-plastic fines (PI < 5%)
D2	Deep Stiff Pleistocene Soil, either **C** (Cohesive) or **S** (Cohesionless)	≤ 1.4	Depth > 200 ft. and < 700 ft. Division between S and C probably not required
D3	Very Deep Stiff Soil	≤ 2.0	Depth > 700 ft.
E1	Medium Thickness Soft Clay	≤ 0.7	Thickness of soft clay layer 10 ft. to 40 ft.
E2	Deep Soft Clay	≤ 1.4	Thickness of soft clay layer > 40 ft.
F	Potentially Liquefiable Sand	≈ 1.0	Holocene loose sand with high water table ($z_w \leq 20$ft.)

The literature of published soil site data was reviewed to identify sites where the amount of subsurface exploration was sufficient for the purposes of both reliably classifying the site (per Table 1) and for performing ground response studies. This effort resulted in the classification of 105 soil sites in California. These sites are listed in Appendix A along with: (1) the sources of the geotechnical data, (2) the classification from this study, (3) the classification by Rodriguez-Marek et al. (where available), (4) the depth to bedrock, as defined on the geologic log, (4) the depth to a shear wave velocity of 600 m/s, and (5) the earthquakes recorded at the site along with the corresponding MHAs. From the list in Appendix A, we sought approximately 9-10 sites having each of the following general characteristics:

I. Shallow stiff soil over rock (soil depth < 30 m): Category C2 in Table 1
II. Moderate depth stiff soil (soil depth = 45-90 m): Category C3 and shallow D1/D2
III. Deep stiff soil (soil depth > 120 m): Category D1, D2 or D3
IV. Soft soil (soft implies $V_s \leq 150$ m/s; soft soil depth > 3 m): Category E

This delineation generally parallels the groupings in Table 1 by using soil depth as a principal factor thought to control site response (with the exception of E). Note that the above is not a proposed new classification scheme, but rather is a convenient grouping of sites for the purpose of this study. The sites and earthquakes selected for analysis are listed in Table 2, along with the range of soil depths actually represented within each group. Seventeen of the recordings are from the 1989 Loma Prieta earthquake, 11 from the 1994 Northridge earthquake, and 8 from other earthquakes.

Table 2: Sites/earthquakes used in this study

I. Shallow Stiff Soil, C2 (soil depth < 30 m)

Capitola (89LP)	Gilroy #7 (89LP)	Petrolia Gen. Store (92CM)
Castaic Dam (94NR)	Halls Valley (89LP)	Potrero Canyon (94NR)
Gilroy Phy. Sci. Bldg. (89LP)	Newhall (94NR)	Simi Valley, Knolls (94NR)

Range of soil depth is 12 to 28 m

II. Moderate Depth Stiff Soil, C3 & Shallow D1/D2 (soil depth = 45-90m)

Arleta F.S. (94NR)	LA, Wadsworth No. (94NR)	Taft, Lincoln School (52KC)
LA, Epiphany Church (94NR)	LA, White Oak (94NR)	
LA, Hollywood Sto. (71SF)	Sylmar, Hospital (94NR)	

Range of soil depths is 49 to 91 m

III. Deep Stiff Soil, Bray D (soil depth > 120m)

El Centro Array #9 (40IV)	LA, Sepulveda VA (94NR)	Palo Alto VA (89LP)
Eureka Apts. FF (92CM)	LA, Wadsworth So. (94NR)	Santa Barbara Court. (78SB)
Gilroy #2 (89LP)	Oakland Outer Harbor (89LP)	Sunnyvale Colton (89LP)
Hollister City Hall (89LP)	Oakland 2-Story (89LP)	

Range of soil depth is 130 to > 244 m

IV. Soft Soil, Bray E (soft soil depth > 3m)

Alameda NAS (89LP)	El Centro #6 (79IV)	Larkspur Ferry (89LP)
Apeel #1 (89LP)	Emeryville (89LP)	Meloland O/C FF (79IV)
Apeel #2 (89LP)	Foster City Menhaden (89LP)	San Francisco Airport (89LP)

Range of soft clay depths (Vs < 150 m/s) is 3 to 27 m

3.0 DEVELOPMENT OF INPUT MOTIONS

This section reviews the means by which input motions were selected for use in ground response analyses for each of the sites/earthquakes listed in Table 2.

3.1 Strong Motion Database

Database development began with the strong motion database for shallow crustal earthquakes in active tectonic regions by Pacific Engineering and Analysis (W. Silva, *personal communication*). The database was augmented with (1) selected free-field motions, and (2) selected recordings from the ground level of building structures. We have not attempted to incorporate all potentially useful structural recordings into the database, this is the focus of a continuing effort by the authors.

For each motion in the augmented database, we attempted to assess the possible influence of near-fault rupture directivity effects. Rupture directivity effects were assumed to be negligible for moment magnitudes, $M_W \leq 6.0$, and site-source distances, $r > 60$ km (N. Abrahamson, 1999, *personal communication*). For motions with $M_W > 6.0$ and $r < 60$ km, the geometric rupture directivity parameters defined in Fig. 1 were obtained from a previous compilation (N. Smith, 1999, *personal communication*), and for sites missing in this compilation, were measured based on published fault rupture models. As shown in Fig. 1, recordings triggered by dip-slip earthquakes but made at sites located off the ends of the fault were assumed to have no rupture directivity effect. Based on the above data, the rupture directivity model for spectral acceleration by Somerville et al. (1997) and modified by Abrahamson (1999, *personal communication*) was invoked to evaluate the expected rupture directivity effect for each site in the database. These effects were expressed using a Rupture Directivity Index (RDI), defined as the amplification/de-amplification of the geometric mean of T = 3 s spectral acceleration due to rupture directivity effects as computed by the Somerville/Abrahamson model. A site experiencing no rupture directivity effect has RDI=1.0. For strike-slip faults, RDI varies from 1.48 (forward directivity), to 0.55 (backward directivity). The range for dip slip faults is 1.16 to 0.72.

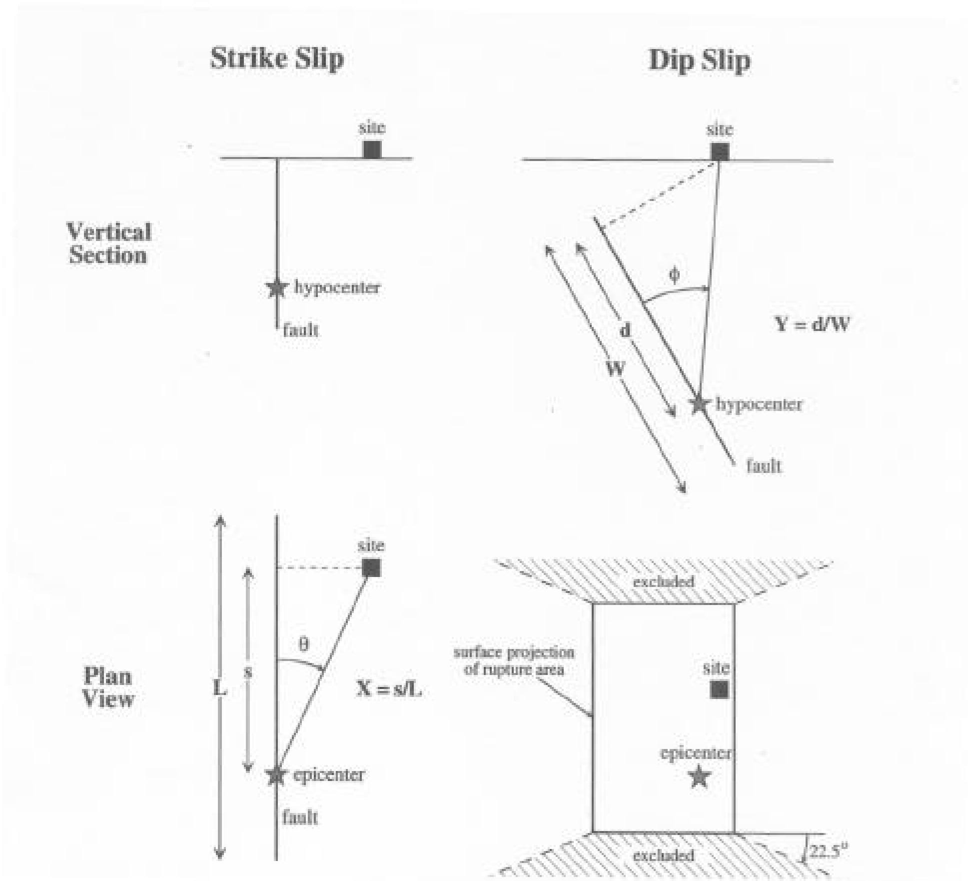

Fig. 1: Rupture directivity parameters for strike-slip faults (X, θ) and dip-slip faults (Y, φ) defined by Somerville et al. (1997)

3.2 Time History Selection Criteria

The database described in Section 3.1 was used to select specific time histories representing possible realizations of the motion that would have been expected at the site had the geologic condition been rock. After appropriate scaling described in Section 3.3, these time histories comprised the input for ground response analyses for the sites listed in Table 2.

The seismological criteria by which these rock time histories were selected are listed below, where the term “target” refers to a characteristic of the causative earthquake for the subject site.

Magnitude: Selected recordings must have been triggered by an event with a magnitude within ± 0.5 of the target.

Amplitude: Time histories were sought that had an MHA within a factor of two to four of the target MHA on rock (evaluation of target MHA on rock is described in Section 3.3).

Site Condition: For relatively deep soil sites, (Types II to IV), time histories were selected from rock sites or C sites with < 20 m of soil (Geomatrix A and B sites). For Type I sites, time histories were selected from only rock sites (Geomatrix A).

Rupture Directivity: Time histories should have RDI’s that are similar to the target RDI. Target RDI is based on site location relative to the fault plane, not deviations of the recorded motion from an attenuation model.

Orientations of time histories that were used in analysis were selected as follows:

- For sites with RDI=1.0 because $M_W \leq 6.0$ or $r > 60$ km, a single random horizontal component of each time history was selected. The ensemble of these random components is intended to represent the geometric mean.
- For sites with RDI≠1.0 and angle θ (strike-slip) or ϕ (dip-slip) < 45 degrees, the model of Somerville et al. (1997) suggests that there is a motion orientation effect associated with the

near-fault wave pattern. Accordingly, time histories are rotated into fault normal and fault parallel components for separate ground response analyses for these two orientations.

- For sites with RDI≠1.0, and angle θ (strike-slip) or φ (dip-slip) > 45 degrees, the Somerville et al. model suggests no significant motion orientation effect. Since many selected time histories for such sites have θ or φ < 45 degrees, we eliminate the orientation effect by using the geometric mean. This is accomplished by retaining both components of an input time history during the ground response analysis, but taking the geometric mean of the computed response as the result.
- For sites with RDI=1.0 because the site is located off the end wall, the Somerville model suggests that motion orientation effects can be present (provided θ, φ < 45 degrees) despite the absence of rupture directivity effects. Hence, time histories are rotated into separate fault normal and fault parallel components.

We did not consider rupture mechanism or hanging wall effects in time history selection. The specific selection criteria and motions for each site are listed in Appendix B.

3.3 Scaling of Input

The time histories selected according to the criteria in Section 3.2 were scaled prior their use in ground response analyses. The intent of the scaling was to provide an ensemble of time histories with median spectral ordinates matching the "best estimate" soft rock spectrum for the subject event and site, while retaining the inherent variability in the estimated rock motion.

The best estimate spectrum is taken as median 5% damped spectral ordinates from the Abrahamson and Silva (1997) rock site attenuation relation, with the following modifications:

- Period dependent event terms provided by Abrahamson (1999, *personal communication*) which quantify event-specific deviations from the general attenuation model.
- Median rupture directivity effects and motion orientation effects as computed by the models in Somerville et al. (1997) and modified by Abrahamson (1999, *personal communication*).
- Removal of near-surface amplification effects at weathered California rock sites. This is accomplished using period-dependent reductions of outcropping rock motion by Idriss (1999) to more adequately represent the motions anticipated on less weathered rock profiles such as occur at depth (i.e. underlying a soil profile).

This best estimate spectrum obtained by these procedures represents the median ground motion that would have been expected at the site had the geologic condition been soft rock. At a particular period, T, this median spectral acceleration is denoted $m_{be}(T)$. The objective of the time history scaling is for the median of the ensemble of time histories, $m_{th}(T)$, to match $m_{be}(T)$.

The scaling of the time histories is performed in two stages. First, individual time history i is scaled up or down by factor $(F_1)_i$ so that its response spectrum, $S_i(T)$, matches $m_{be}(T)$ in an average sense over the range T=0-1 s. Denoting the median spectra of the scaled time histories as $m_{sth}(T)$ [i.e., $m_{sth}(T)$ is the median of $S_i(T)$´ $(F_1)_i$ across all i], a set of period-dependent scaling factors are defined as:

$$F_2(T) = \frac{m_{be}(T)}{m_{sth}(T)} \quad (1)$$

The second scaling consists of time domain response spectral matching of each individual time history i to a target spectrum that is $S_i(T)$´ $(F_1)_i$´ $F_2(T)$. The time domain response spectral matching is performed with the program RSPMATCH (Abrahamson, 1998).

The above procedure ensures that the median spectral ordinates of the twice scaled time histories match the best estimate spectrum, $m_{be}(T)$. Further, the inherent variability across the time histories is preserved. Shown in Appendix B for each site/earthquake in Table 2 are the best estimate spectrum (from modified attenuation) along with the median and median ± one standard error of the twice scaled input rock motions (assuming log-normal distribution). For every site, the match between the median rock time histories and best estimate spectrum is excellent.

4.0 GROUND RESPONSE MODELING

Ground response modeling was performed using an equivalent-linear characterization of dynamic soil properties as implemented in the program SHAKE91 (Idriss and Sun, 1992) which is a modified edition of the original SHAKE program (Schnabel et al., 1972). The program computes the response of a horizontally layered soil deposit over a uniform half-space subjected to vertically propagating shear waves. This modeling only accounts for one-dimensional ground response effects. Two-and three-dimensional factors such as basin response, topographic amplification, and surface waves are not considered. The following sections review several important details of the SHAKE91 analyses.

4.1 Dynamic Soil Properties

The characterization of soil conditions for each site consists of specifying: (1) a profile of small strain shear wave velocity (V_S), and (2) relationships for the variation of normalized shear modulus (G/G_{max}) and hysteretic soil damping (b) with shear strain (g) within the soil. For each of the sites selected for this study, V_S profiles were obtained from in situ measurements by either downhole or suspension logging techniques. Specific sources of V_S data for each site are listed in Appendix B. Modulus reduction and damping curves were specified on the basis of soil type as indicated in Table 3. The specific curves selected for materials at each site are indicated on the geologic logs in Appendix B.

Table 3: Criteria for selection of modulus reduction and damping curves.

Soil Type	Condition[1]	Reference
Sand and silty sand	Z < 100 m	Seed et al. (1984), upper bound sand G/G_{max}, lower bound b
	Z > 100 m	EPRI (1993): Z=251-500 ft.
Clays, silty clays, loams	PI = 15 & Z < 100m	Vucetic and Dobry (1991), PI=15[2]
	PI = 15 & Z > 100 m	Stokoe (1999), CL curve, Z = 100-250 m
	PI ≥ 30	Vucetic and Dobry (1991)
	Bay Mud	Sun et al. (1988)
	Old Bay Clay	Vucetic and Dobry (1991), PI=30[3]
Bedrock	$V_S < 900$ m/s	Use soil curves for appropriate material type, depth, and PI
	$V_S > 900$ m/s	Schnabel (1973)

[1]Z=depth, PI = plasticity index

[2] Consistent with Stokoe (1999), CL curve, Z < 100 m

[3] Consistent with Guha et al. (1993) material testing

It should be noted that the dynamic soil properties at the subject sites were fixed at the values indicated in Appendix B, and no variability in soil properties was considered. The effect of soil property variability on uncertainty in soil site ground motions has been investigated by others (Roblee et al., 1996; EPRI, 1993). The effects are most pronounced at $T < 1$ s, and obviously increase in significance with the level of uncertainty in soil properties (i.e., these effects are less significant for well characterized sites, such as the sites considered in this study). These effects are being investigated in a parallel study by Silva (1999) in the FY 1998-99 PEER-PG&E research program, and hence were not a focus of this study.

4.2 Location of Control (Input) Motion

As described in Section 3.2, we selected time histories from rock sites for use as input in ground response analyses. Accordingly, control motions were input at or slightly below soil-bedrock interface for sites where this depth is known or could be estimated. However, for several sites in the San Fernando, Imperial, and Santa Clara basins, bedrock occurs at depths beyond the practical limits of geotechnical subsurface exploration, and hence little data exists from which to estimate dynamic soil properties at depth. These sites are Arleta, Eureka, El Centro Array #6 and #9, Hollister, Meloland, Santa Barbara, Sepulveda VA, and Sunnyvale. For these sites, the base of the ground response model is in soil, calling into question the appropriateness of using rock time histories as input.

The other option, of course, is to use input time histories recorded at soil sites. Attenuation relationships indicate that ground motions on soil are richer in long period energy than ground motions on rock (e.g. Abrahamson and Silva, 1997). Recent studies have suggested that much of the ground response effect (which creates the difference between rock and soil motions) is controlled by the upper 30 m of soil (Borcherdt, 1994). While this finding remains controversial (e.g. Anderson et al., 1996), it seems reasonable to postulate that near-surface soils (tens to ~100 m depth) with relatively low shear wave velocities (V_S <~600 m/s) exert a stronger influence on one-dimensional site amplification than the deeper, stiffer basin structure. Accordingly, the use of soil site recordings as input motions for ground response analyses would be expected to overestimate the long period components of ground motion on soil.

Based on this reasoning, we elected to use time histories recorded at rock sites for input motions in ground response models that terminate in soil. In each such case, the soil profile was extended to depths where increases in V_S with depth are relatively gradual. Shear wave velocities in soil at the base of each such profile were greater than about 600 m/s, with the exception of the El Centro Array sites where $V_S \approx 450$ m/s.

4.3 Analysis of Strain-Dependent Soil Properties

SHAKE91 analyses are performed for one direction of shaking, hence consideration must be given to which ground motion component is used to calculate the equivalent linear soil properties. Some of the sites considered in study are subject to near-fault directivity effects in which fault normal motions exceed fault parallel motions at long periods (spectral ordinates for $T < 0.6$ s are identical for both horizontal directions). For these sites, dynamic soil properties are estimated based on the ground response analysis for the fault normal direction, and these properties are applied for the calculation of fault parallel ground response (for which the calculated shear strains would otherwise be smaller).

For sites subject to near-fault effects but for which the fault normal/fault parallel ratio is expected to be unity based on the Somerville et al. (1997) model, the geometric mean of the calculated response from the two horizontal components is used. In these cases, dynamic soil properties are separately evaluated for the two horizontal directions. For non near-fault sites, only one randomly oriented horizontal component of input motions is used.

5.0 STATISTICAL ANALYSIS OF RESULTS

5.1 Analysis

In this section, we compare 5% damped spectral accelerations of recorded time histories on soil to estimated spectra from: (1) a modified soil attenuation relationship and (2) ground response analyses. Estimated spectra by both methods are represented in terms of their median value and their standard error term in natural log units.

The first estimate of soil spectra is taken using the Abrahamson and Silva (1997) soil attenuation relation, with modifications for event terms and near-fault effects as described previously for rock sites in Section 3.3. For soil site j in site category i, the natural logs of the median spectral ordinates obtained by the modified attenuation relation are denoted $A_{ij}(T)$, and the standard error term is denoted $[s_a(T)])_{ij}$. Since all the median and standard error terms considered here have a functional dependence on period, this will be dropped in subsequent nomenclature. The second estimate of soil spectra is from ground response analysis. Again considering soil site j in site category i, the natural log of the calculated spectra using input motion k is denoted $(G_{ij})_k$. Taking N_j as the number of input time histories used in ground response analyses for site j, the median and standard error of $(G_{ij})_k$ for k=1..N_j are denoted G_{ij} and $(s_g)_{ij}$, respectively. Hence, for soil site j in site category i, the two statistical estimates of computed soil spectra are denoted:

	Attenuation	Ground Response Analysis
Median	A_{ij}	G_{ij}
Standard Error	$(s_a)_{ij}$	$(s_g)_{ij}$

In Appendix B are plots for each site of the exponent of A_{ij} & $A_{ij}\pm(s_a)_{ij}$ and G_{ij} & $G_{ij}\pm(s_g)_{ij}$ vs. period.

Denoting the natural log of the recorded, or "observed," ground motion as O_{ij}, residuals between the estimated median spectra (i.e., "*m*" spectra) and observed spectra for soil site j in site category i are taken as:

$(r_{g1})_{ij} = O_{ij} - G_{ij}$: residual, *m* estimate, ground response

$(r_{a1})_{ij} = O_{ij} - A_{ij}$: residual, *m* estimate, modified soil attenuation (1)

We also consider a separate, median plus one standard error estimate of ground motion (i.e. the "m+s" spectra). Residuals of these ground motion estimates are taken as:

$(r_{g2})_{ij} = O_{ij} - \left(G_{ij} + (s_g)_{ij}\right)$: residual, m+s estimate, ground response

$(r_{a2})_{ij} = O_{ij} - \left(A_{ij} + (s_a)_{ij}\right)$: residual, m+s estimate, modified soil attenuation (2)

Median minus one standard error ground motion estimates were also considered, but were found to be poor predictors of observed ground motion at all periods, and hence are not carried forward. In Appendix B are plots for each site of $(r_{a1})_{ij}$ & $(r_{a2})_{ij}$ and $(r_{g1})_{ij}$ & $(r_{g2})_{ij}$.

The medians and standard errors of residuals within category i are taken across the j=1..M_i sites (assuming category i to have M_i sites). These statistical quantities are denoted as follows:

$(R_{g1})_i$, $(s_{g1})_i$ = median, standard error of $(r_{g1})_{ij}$

$(R_{a1})_i$, $(s_{a1})_i$ = median, standard error of $(r_{a1})_{ij}$ (3)

Similar definitions apply for the median plus one standard error ground motion estimates, with "2" replacing "1" in the subscripts in Eq. 3. Since the number of sites in each category (M_i) is fairly small (7-11), the uncertainty in the estimates of median quantities $(R_{g1})_i$ & $(R_{g2})_i$ and $(R_{a1})_i$

& $(R_{a1})_i$ should be considered. Statistical theory indicates this uncertainty in these medians can be estimated as (Ang and Tang, 1975),

$$\left(\bar{s}_{g1}\right)_i^2 = \left(s_{g1}\right)_i^2 / M_i \tag{4}$$

where $\left(\bar{s}_{g1}\right)_i$ denotes the standard error of the estimate of $(R_{g1})_i$. Similar definitions apply for the other median quantities considered.

Figures 2 (a)-(d) present the variation of category median residuals ($R_{g1-2} \pm \bar{s}_{g1}$ and $R_{a1-2} \pm \bar{s}_{a1}$) and category standard errors (s_{g1-2} and s_{a1-2}) with period, T. Table 4 summarizes average residuals of m and $m+s$ ground motion estimates across period ranges $T \leq 1.0$ s and $T > 1.0$ s.

5.2 Interpretation

We begin our interpretation of the results by focusing on E sites, for which the trends are most clearly defined. Referring to Fig. 2(d) and Table 4, two principal findings emerge from the category statistics:

1. *Benefit of ground response analysis*: The benefit of performing ground response analysis is measured by comparing category residuals and standard errors for the m ground response and soil attenuation ground motion estimates. Both category residuals and standard errors are smaller for the ground response estimates for $T <\sim$ 1-2 s. The smaller residual means that ground response analyses more accurately predict ground motions, and the smaller standard error means that the residuals are more consistent across sites in the category. Of the two benefits, the reduction in standard error is most pronounced.

Table 4a: Average category residuals and standard errors of median (m) ground motion estimates

Site Category	Average Category Residual[1] ($T \leq 1.0$ s)		Average Category Residual[1] ($T > 1.0$ s)		Average Category Standard Error ($T \leq 1.0$ s)		Average Category Standard Error ($T > 1.0$ s)	
	R_{g1}	R_{a1}	R_{g1}	R_{a1}	s_{g1}	s_{a1}	s_{g1}	s_{a1}
I (C2)*	0.03 ± 0.17	0.22 ± 0.16	0.30 ± 0.25	-0.08 ± 0.20	0.47	0.44	0.71	0.55
II (C3, shallow D1/D2)	0.15 ± 0.19	0.28 ± 0.12	0.75 ± 0.17	0.38 ± 0.17	0.49	0.32	0.44	0.46
III (deep D)	0.29 ± 0.14	0.34 ± 0.15	0.58 ± 0.17	0.19 ± 0.17	0.45	0.48	0.57	0.57
IV (E)	0.39 ± 0.09	0.54 ± 0.23	0.25 ± 0.14	0.11 ± 0.16	0.28	0.68	0.41	0.49

Table 4b: Average category residuals and standard errors of $m+s$ ground motion estimates

Site Category	Average Category Residual[1] ($T \leq 1.0$ s)		Average Category Residual[1] ($T > 1.0$ s)		Average Category Standard Error ($T \leq 1.0$ s)		Average Category Standard Error ($T > 1.0$ s)	
	R_{g2}	R_{a2}	R_{g2}	R_{a2}	s_{g2}	s_{a2}	s_{g2}	s_{a2}
I (C2)*	-0.30 ± 0.17	-0.26 ± 0.16	-0.37 ± 0.25	-0.69 ± 0.20	0.48	0.44	0.75	0.56
II (C3, shallow D1/D2)	-0.16 ± 0.20	-0.22 ± 0.12	0.15 ± 0.20	-0.24 ± 0.18	0.53	0.32	0.53	0.47
III (deep D)	0.00± 0.14	-0.17± 0.15	-0.16± 0.18	-0.43 0.18	0.45	0.51	0.60	0.58
IV (E)	0.07± 0.09	0.03± 0.24	-0.46± 0.13	-0.53 0.16	0.27	0.72	0.40	0.49

[1]Error terms are standard errors of the median (Eq. 4)

*omitting Potrero Canyon

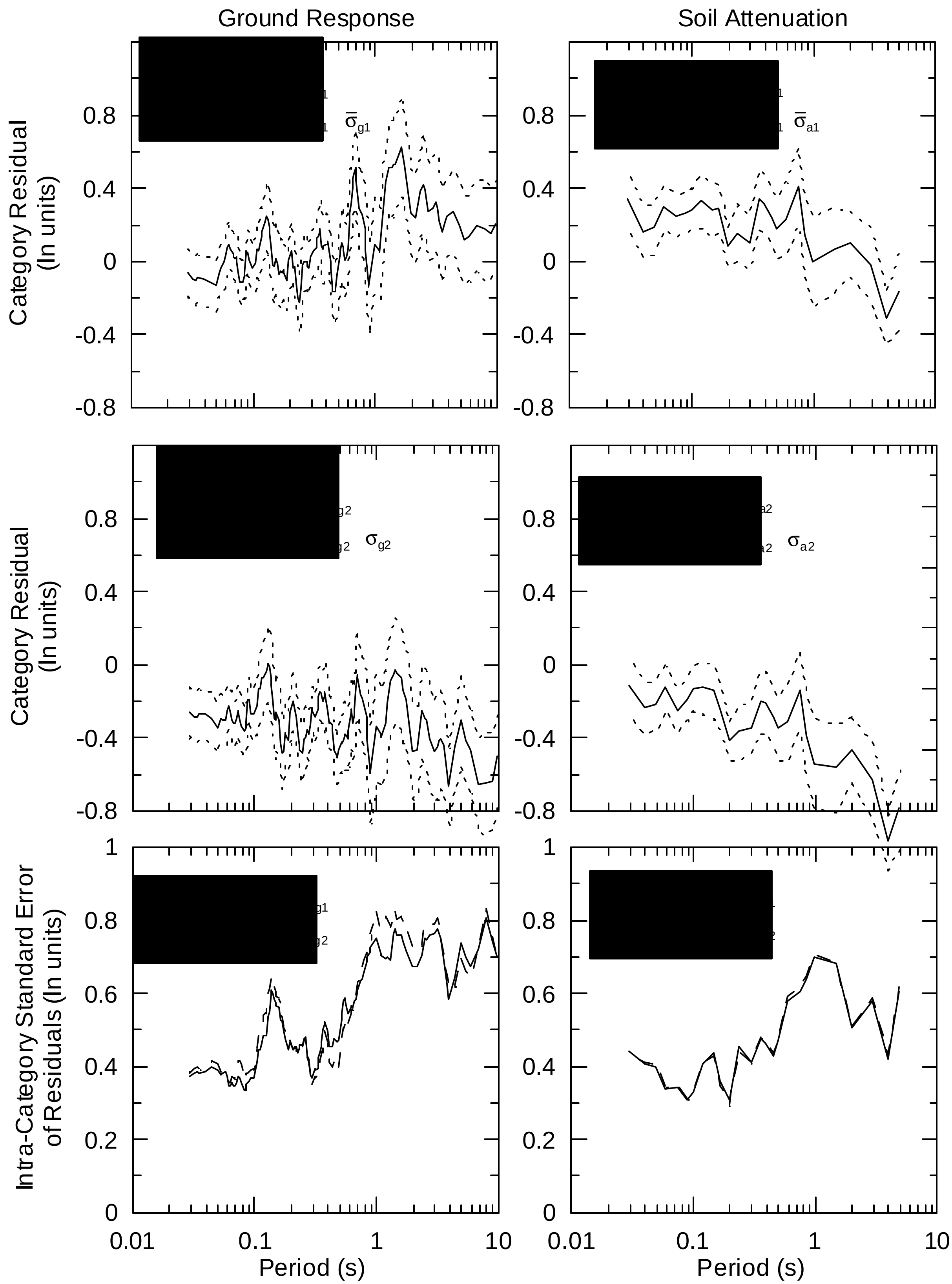

Fig. 2(a): Category median residuals and standard error terms, Type I sites (C2, Soil Depth < 30 m)

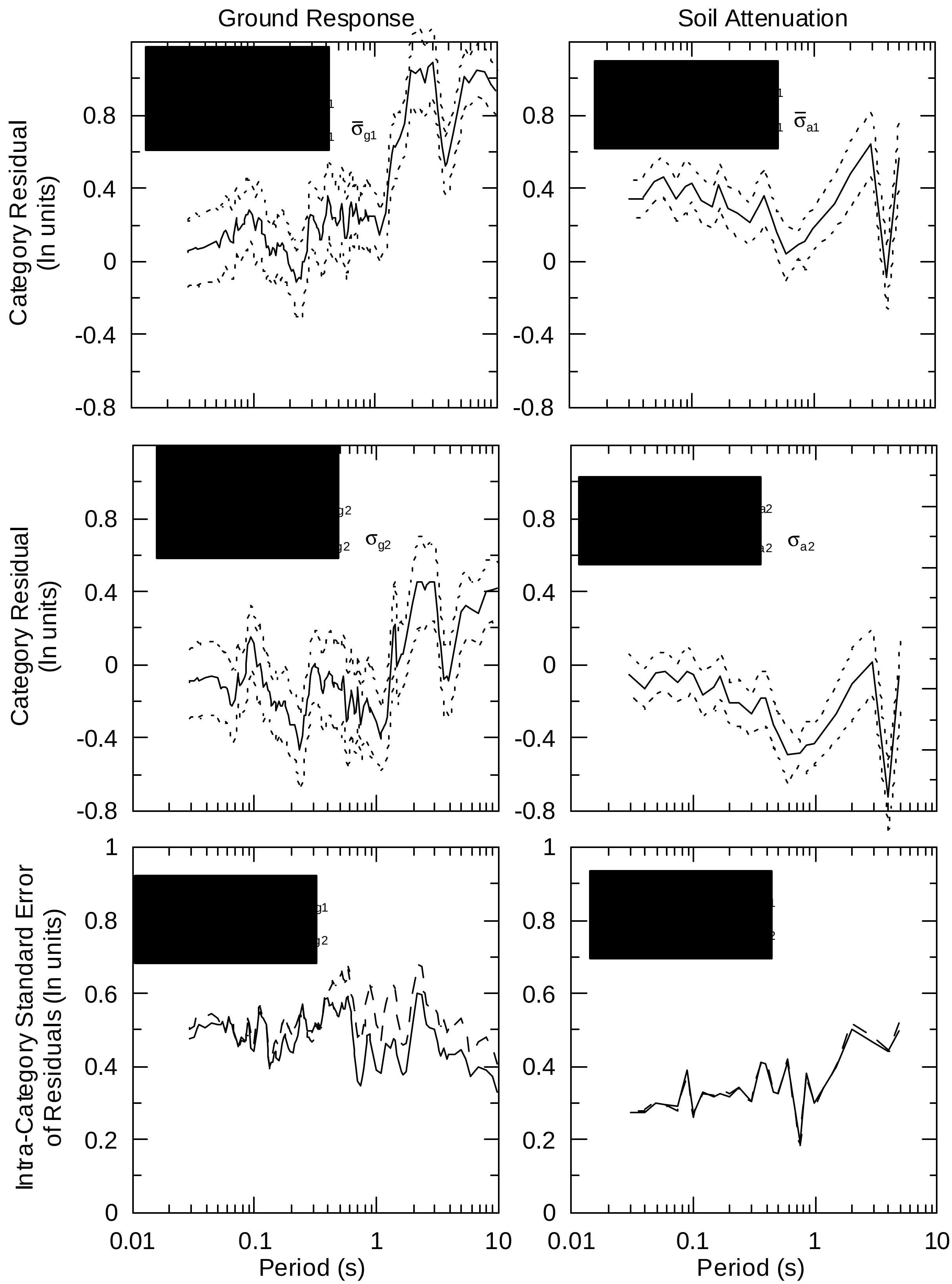

Fig. 2(b): Category median residuals and standard error terms, Type II sites (C3 & shallow D1/D2, Soil Depth = 45-90 m)

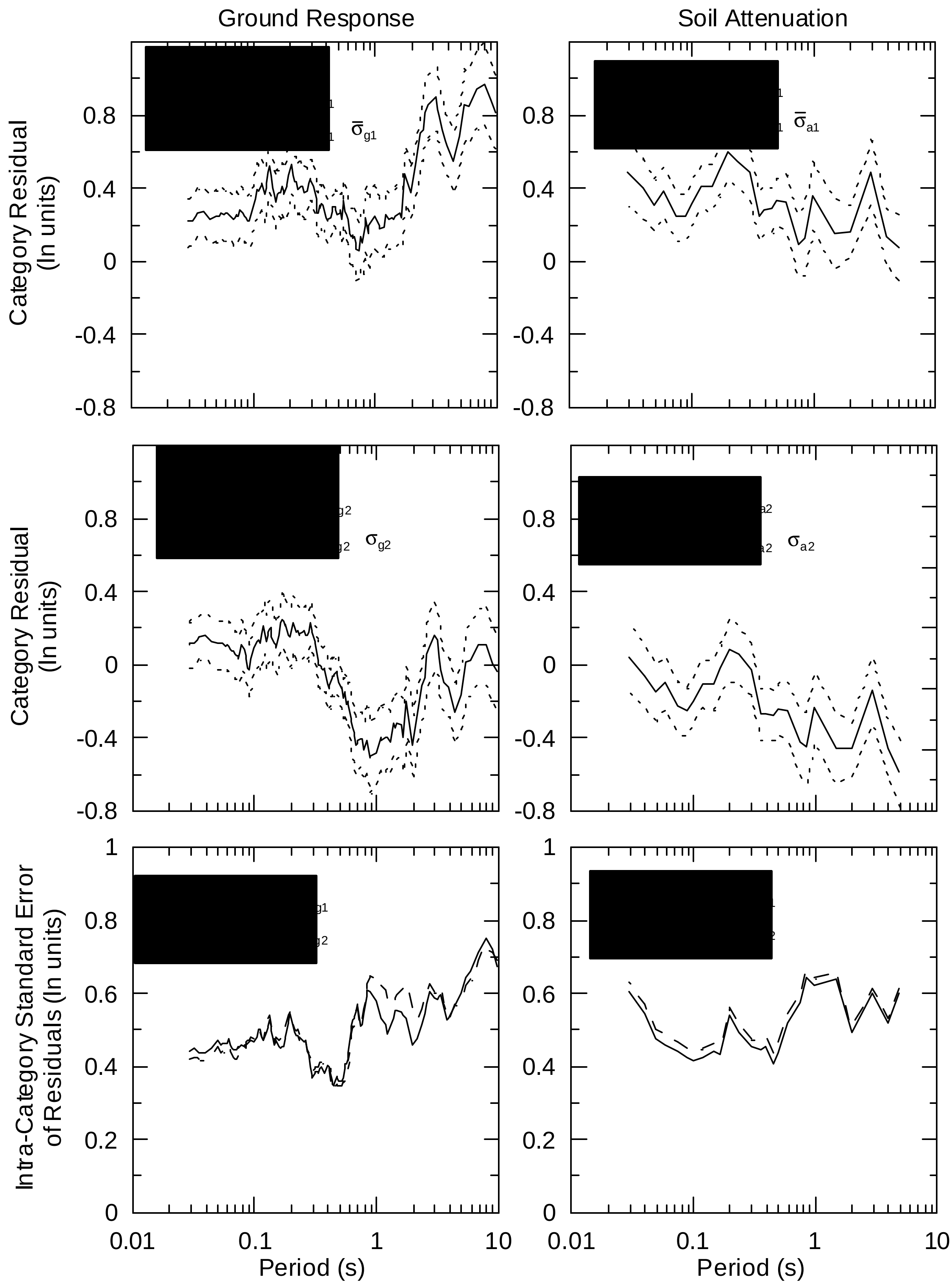

Fig. 2(c): Category median residuals and standard error terms, Type III sites (Deep D, Soil Depth > 120 m)

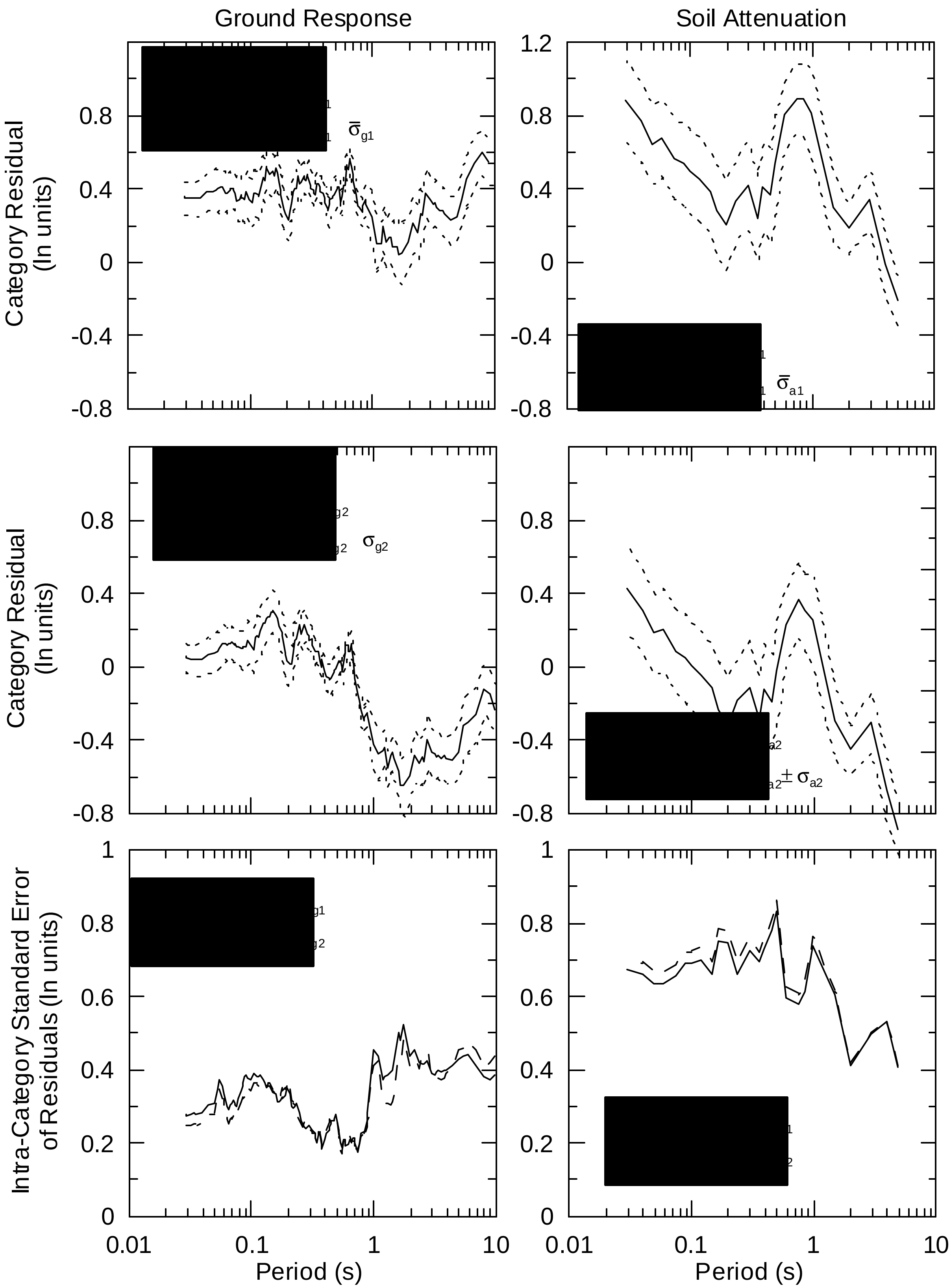

Fig. 2(d): Category median residuals and standard error terms, Type IV sites (E, Soft Soil Depth > 3 m)

2. *Bias in ground response results*: The category residuals for the m ground response estimates are non-zero with a high level of confidence for $T < \sim 1$ s. Across this period range, the $m+s$ estimate has much smaller residuals (average of 0.06 as compared to 0.36 for m). At longer periods, the results are less consistent, although the m estimate preliminarily appears to be reasonable.

With respect to the first comment above (benefit of ground response), site categories other than E exhibit mixed trends. For $T \leq 1$ s, m ground response estimates have smaller residuals than m soil attenuation estimates in all site categories. The residual reduction for m ground response estimates at $T \leq 1$ s is modest for deep D and C3/shallow D, but is relatively pronounced for C sites. The significant uncertainty reduction observed in ground response results for E sites is not observed for other site categories. Comparing averaged s_{g1} and s_{a1} values in Table 4a, ground response is seen to provide lower uncertainty for deep D sites, but s_{g1} is actually larger than s_{a1} for C3/shallow D and C2 sites. These results indicate that while ground response generally provides more accurate spectra for these site classes (i.e., $R_{g1} < R_{a1}$), there is a relatively high level of uncertainty in the amount of bias in computed spectra. This means that the ground response procedures are modeling ground motion variations between sites relatively poorly, implying that other factors are significantly affecting these variations (e.g., source and path effects).

The bias observed at E sites in the m ground motion estimates for $T < \sim 1$ s is also present at deep D and C3/shallow D sites. No significant bias is observed for $T \leq 1$ s at C2 sites. Median attenuation estimates are also biased for $T \leq 1$ s in all site categories, indicating that motions in each category exceed the median values for soil sites. Nonetheless, based on the results presently available, the following usage of ground response analysis results appears to provide the smallest residuals for $T \leq 1$ s:

C2:	m estimate
C3/shallow D1/D2:	m+0.5s estimate
Deep D:	m+s estimate
E:	m+s estimate

The cause of the bias for the last three site categories is not well understood. However, since m residuals for soil attenuation estimates are also positive, some of the bias may be attributable to underestimates of the input (rock) ground motion amplitudes (i.e., median rock attenuation ordinates from which the "best estimate" target spectrum is derived may be low). The bias may also be partially attributable to errors associated with the use of the equivalent linear method of ground response computation, or errors in the selection of dynamic soil properties. It is noted that ground motion estimates at small periods (where the bias is most consistently observed) are especially sensitive to soil hysteretic damping ratio, b. Overestimation of b would cause an underestimation of ground response that would increase with soil thickness (because for a given frequency more wavelengths subject to soil damping will be present in thicker soil deposits). This trend is observed in the data, i.e. R_g increases with increasing depth of soil.

For $T > 1$ s, the m ground response estimate provides large residuals for deep D and C3/shallow D sites, implying that the ground response models are not capturing the long-period components of the ground motions. This is not surprising, as many of the sites in these categories are near basin edges where basin edge effects can be significant at large periods. The bias in this period range for m soil attenuation is smaller, implying that basin effects are to some degree represented in the empirical database for soil sites. Further, no significant long period bias is observed in m ground response estimates at C2 sites, where basin edge effects would generally not be expected.

The observed significance of site response effects for E sites, and to some extent deep D sites, is consistent with many previous studies that have focused on sites within these categories (e.g., Seed and Dickenson, 1996; Chang, 1996; Idriss, 1990; Darragh and Idriss, 1997). In addition, the large s_g values for the deep D and C3/shallow D categories appear to be consistent with Lee's (1996) finding that ground response effects are generally small relative to source/path effects at soil sites in southern California.

Finally, it should be noted that the results summarized in Fig. 2 and Table 4 are for a limited number of sites within each category. Many more sites should be added within each category to enable more stable and robust estimates of the category residuals and standard errors terms. Such work could change somewhat the findings reported above.

6.0 SENSITIVITY OF GROUND RESPONSE TO INPUT SCALING PROCEDURES

6.1 Importance of Rock Correction Factors

As noted in Section 3.3, the target response spectrum for the median of the scaled time histories includes a correction to account for amplification in the near-surface weathered zones of outcropping rock sites. As shown in Fig. 3, the correction reduces the amplitude of the target spectrum at low periods. Fig. 4 shows the impact of this correction on the computed response of a deep stiff soil site (Palo Alto VA Building) and shallow stiff soil site (Castaic Dam Toe).

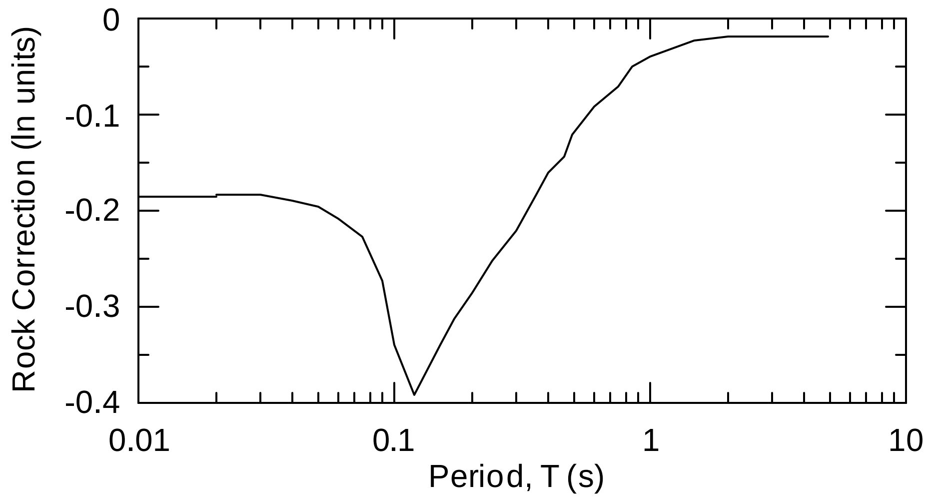

Fig. 3: Response spectral scale factor to correct rock attenuation relations (after Idriss, 1999)

Shown in Figs. 4(a)-(b) are median computed responses (i.e., exponent of G_{ij}) from the ensemble of time histories for these sites, with and without corrections to the input target rock spectra, along with the spectra of the recorded motions (which happen to be fault normal components). Also shown in Figs. 4(a)-(b) are residuals of the computed spectral accelerations evaluated as per Eq. 1 (i.e., $(r_{g1})_{ij}$). Fig. 4(c) shows the difference between the residuals with and without the rock outcrop correction for the two sites. Despite the large difference in the soil conditions and ground responses at these two sites, the effects of the rock correction on the computed motions for both sites are similar. This residual difference is about 0.2 for $T < \sim 0.2$ s, and decreases to essentially null at about $T = 1 - 2$ s. This difference could explain much of the bias noted in Section 5.2 for the C3/shallow D and deep D site categories. However, other considerations could also explain the bias, and no firm conclusions can be drawn at present.

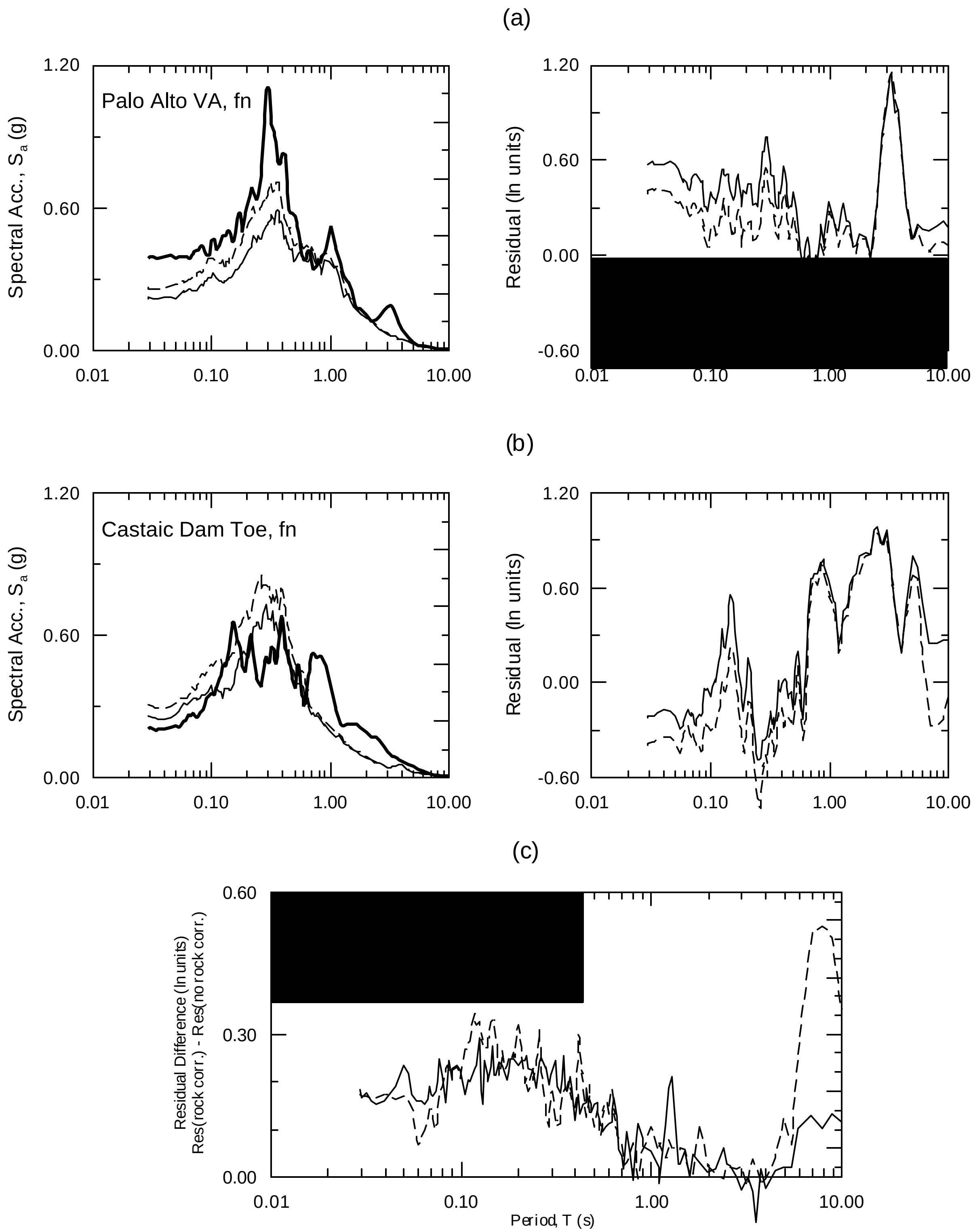

Fig. 4: (a) Spectra and residuals with and without rock correction to input, Palo Alto VA
(b) Spectra and residuals with and without rock correction to input, Castaic Dam
(c) Comparison of rock correction effect on residuals

6.2 Use of Spectrum Compatible Input Motions to Evaluate Median Ground Response

Scaling procedures for input time histories used in this study were described in Section 3.3. The intent of the scaling was to provide an ensemble of time histories with a median spectral response matching the "best estimate" soft rock spectrum for the subject event and site, while retaining the inherent variability in the estimated rock motion. Here we investigate an alternative time history scaling procedure, which consists of modifying each time history in the time domain such that its response spectrum fully matches the target (Abrahamson, 1998). Using the site-specific target spectrum and input time histories developed according to the procedures described previously, a comparison is made as follows. The time histories are scaled once according to the criteria set forth in Section 3.3 (Suite 1, denoted as "scaled"), and again using time-domain response spectral matching procedures to fully match each time history to the target spectrum (Suite 2, denoted as "spectrum compatible"). Ground response analyses are performed using both suites of scaled motions. The natural log is taken of spectral ordinates near the site period, and for each period the median spectral ordinate from n of the time histories is calculated. Plotted in Fig. 5 is the average of the median spectral ordinates across the period range indicated as a function of n, which is varied from 3 to N_j. This exercise is carried out for the following sites (one site per category): Castaic, Sylmar, Palo Alto VA, and Larkspur.

The results indicate that ground response analyses using spectrum compatible time histories converge to a stable median with as few as 3 time histories, whereas results from the "scaled" suite require on the order of 10-15 time histories to converge. Not surprisingly, the standard error of the median is relatively low with the spectrum compatible results. The Larkspur and Palo Alto sites indicate a positive bias in spectrum compatible results, but this effect is not observed at Castaic and Sylmar, and no firm conclusions about a bias can be drawn at present.

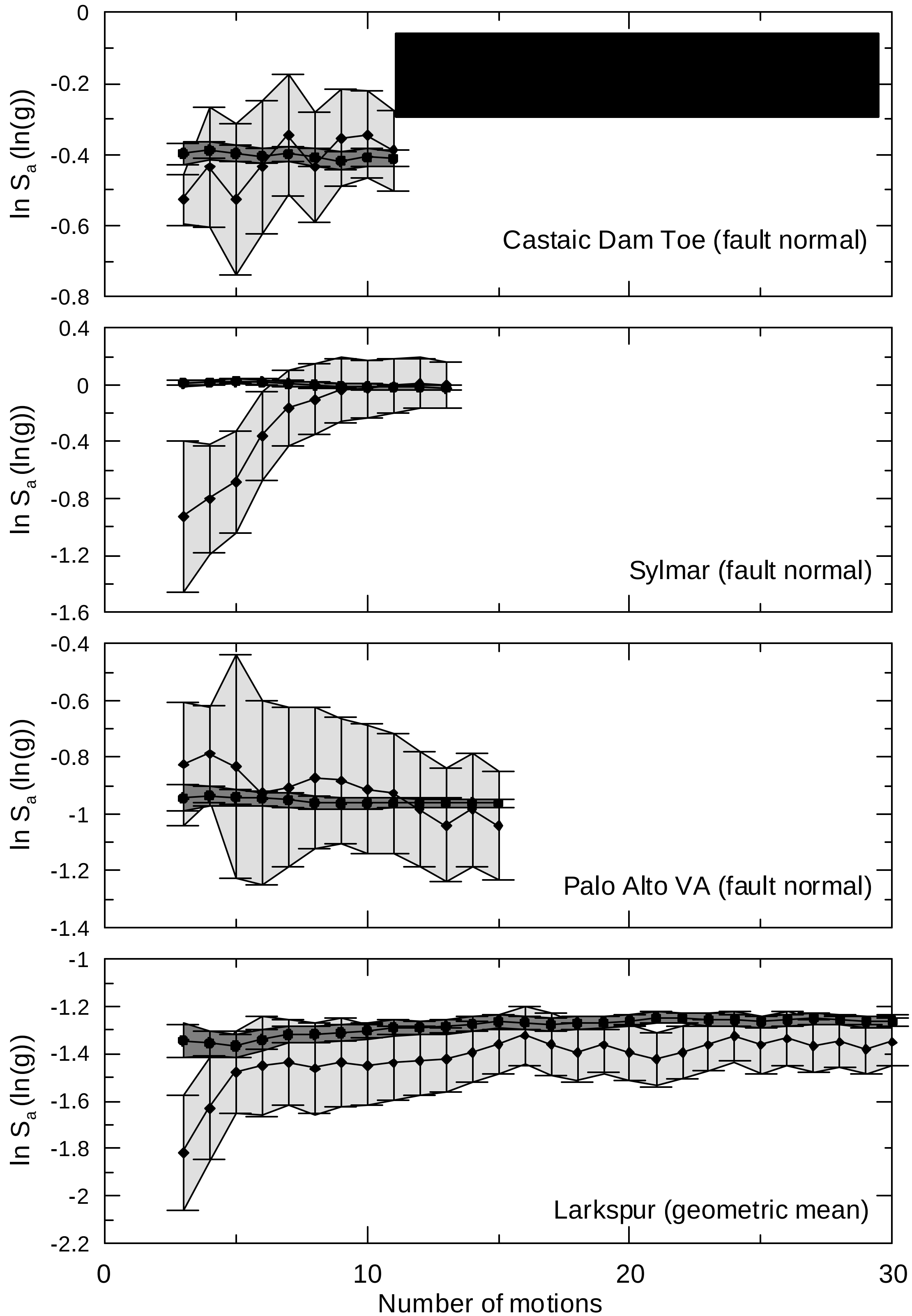

Fig. 5: Comparison of scaled and spectrum compatible median spectral accelerations

7.0 SUMMARY AND CONCLUSIONS

In this study we have estimated ground motions for accelerograph stations on soil using ground response analyses and a modified version of the soil attenuation relationship by Abrahamson and Silva (1997). Residuals between recorded and estimated motion were calculated to elucidate trends in the results of each ground motion estimation procedures across geotechnical site categories. For $T < 1$ s, we find that ground response analyses improve the accuracy of ground motion predictions relative to attenuation in all site categories. However, the uncertainty in the residual of the estimated ground motions is large for C and D sites, indicating that factors other than site response are “randomly” varying the motions from site-to-site. We interpret this as evidence for a strong influence of source and path effects on soil site ground motions. Conversely, for E sites, the standard error of ground response estimates is small, indicating a strong and systematic influence of ground response that is reasonably well captured by the analysis.

For $T > 1$ s, substantial positive bias is observed in median ground response results for D sites, which may be a basin effect. Ground motion estimates from soil attenuation relations are more accurate within this period range for D sites. A somewhat surprising result from this study is a consistent bias for $T < 1$ s in ground response results for site categories other than C2. Given this bias, our recommendation for the interpretation of ground response results is that median plus one standard error ground motions be used for E and deep D sites if the input is scaled to the median rock motion. For C3/shallow D and C2 sites, median plus half-standard error and median ground motions should be used, respectively.

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APPENDIX A

SOIL SITES WITH WELL CHARACTERIZED GEOTECHNICAL CONDITIONS

AND STRONG MOTION RECORDINGS IN CALIFORNIA

Acknowledgements

The work described in this report was funded by the Pacific Earthquake Engineering Research (PEER) Center under the Pacific Gas & Electric Company Contract No. 09566. This financial support is gratefully acknowledged.

This work made use of Pacific Earthquake Engineering Research Center Shared Facilities supported by the Earthquake Engineering Research Center Program of the National Science Foundation under Award Number EEC-9701568.

The financial support of the PEARL sponsor organizations including the Pacific Gas & Electric Company (PG&E), the California Energy Commission (CEC), and the California Department of Transportation (Caltrans) is acknowledged.

We would like to thank Nancy Smith and Paul Somerville URS Greiner Woodward Clyde, Pasadena Office, for providing rupture directivity parameters for strong motion stations. Thanks are also extended to Walt Silva of Pacific Engineering and Analysis and Norm Abrahamson of PG&E for helpful comments made in numerous discussions about this topic. We appreciate the efforts of Andrew Liu of UCLA, who helped prepare input files for ground response studies.